PROGRESS IN U.S. PHOTOVOLTAICS: LOOKING BACK 30 YEARS AND LOOKING AHEAD 20

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ABSTRACT

The development of terrestrial photovoltaics (PV) began in response to the oil crises of the 1970s. Over the past 30 years, PV researchers discovered new materials, devices, and fabrication approaches, improved device efficiency and reliability, and lowered module and system costs. Concerns over the global environment, as well as the worldwide efforts to seek alternate, indigenous sources of energy, continue to drive the investment in PV research and deployment. This paper reviews the most significant advances in U.S. research efforts over the past 30 years, and examines several scenarios for advancements in PV technologies and markets in the next 20 years.

1. INTRODUCTION

The author's career in photovoltaics began 30 years ago when he joined a team of researchers at Harvard University and Tyco Laboratories (Waltham, MA) to investigate the growth of silicon ribbons by the edge-defined film-fed growth (EFG) process for terrestrial PV applications. This was one of the first solar energy projects funded by the National Science Foundation in response to the looming oil crisis. After five years, the author joined the Solar Energy Research Institute (SERI) in Golden, Colorado, renamed the National Renewable Energy Laboratory (NREL) in 1991. At SERI/NREL, the author has been involved with management of the NREL Photovoltaics Program, a significant part of the U.S. Department of Energy (DOE) National Photovoltaics Program.

Through these efforts, the author had a unique opportunity to have first-hand insight into most, if not all, U.S. PV research activities over the past 30 years, as well as being an active participant in planning and carrying out research programs funded by DOE/NREL. This paper provides a brief overview of these insights, starting with the author's perspectives on U.S. PV activities over the past 30 years. The next section covers the major trends in research progress, followed by a decade-by-decade view of key developments in the U.S. DOE PV Program, and advances in research, technology, and markets for PV. The final section provides the author's perspectives for the next two decades, looking at various projections for progress in PV technologies and markets.

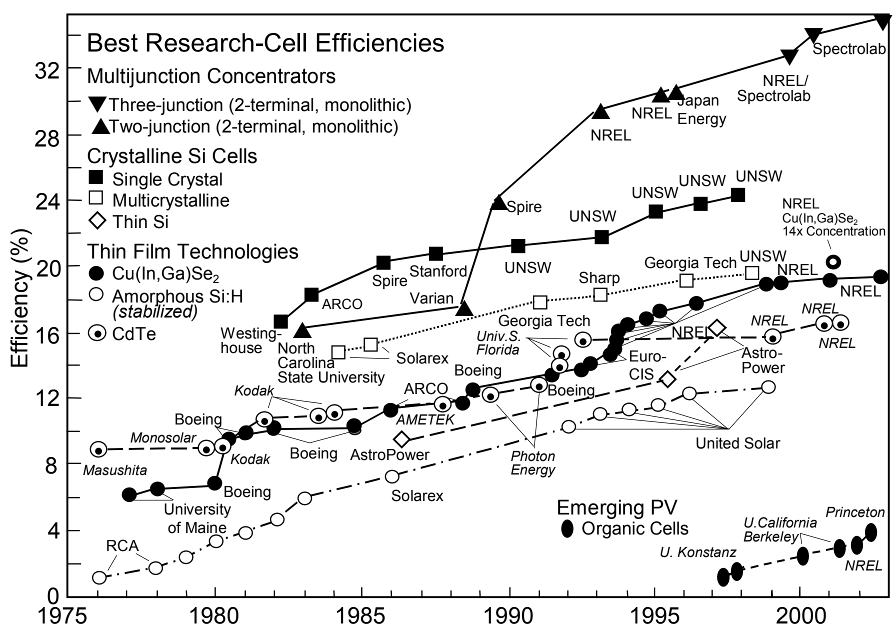

Figure 1: Progress in solar cell efficiencies (1976 to present) for various research or laboratory devices. All these cell efficiencies have been confirmed and were measured under standard reporting conditions.

2. LOOKING BACK 30 YEARS

This paper is not intended to be a comprehensive review of U.S PV research activities over the past 30 years. Rather, a brief overview is presented of the major trends in research and the markets, followed by a decade-by-decade overview of the key programmatic thrusts, research accomplishments, and progress in technology and the markets. The focus is on U.S. programs and research progress, but some worldwide results are presented, where appropriate, to provide context for the U.S. efforts. It should be mentioned at the outset that these perspectives on past accomplishments, and especially on future projections, are strictly those of the author and do not represent the views of DOE or NREL. Indeed, many PV experts would likely differ in their views of both past accomplishments and future projections.

2.1 Major Trends

One of the most significant trends over the past 30 years – one that is undeniably one of the best measures of the success of PV research – is the continuous improvement of solar cell efficiencies for all technologies over the years (see Fig. 1). A number of these technologies, specifically thin films and multijunction concentrator cells, owe their genesis to the U.S. PV research programs. In fact, U.S. researchers have led the development and continue to hold the world-record efficiencies in these technologies. This is not meant to imply that worldwide researchers have not achieved equally remarkable results. Among the most noteworthy accomplishments in Fig. 1 are the 24.7%-efficient crystalline silicon solar cell (University of New South Wales [UNSW], Australia), the 19.2%-efficient copper indium gallium selenide (CIGS) solar cell (NREL), and the 35.2%-efficient $GaInP_2$/GaInAs/Ge triple-junction solar cell under 66-suns concentration (Spectrolab). While these and the other results in Fig. 1 are clearly important, significant differences remain between the best performances and the theoretically predicted values for each solar cell technology. Furthermore, the efficiencies of commercial (or even the best prototype) modules are only about 50% to 65% of these "champion" cells. Closing these gaps is the subject of ongoing and future research.

Research efforts have also resulted in improvements in the second significant metric, namely the manufacturing cost of photovoltaic modules. Figure 2 shows the results of an annual survey conducted by DOE/NREL's Photovoltaic Manufacturing R&D Project. This is a government/ industry research partnership of some 15 U.S. PV companies, with the goal of reducing manufacturing costs and significantly scaling up U.S. PV module production capacity. Over the past 11 years, DOE and industry have invested more than $140 million in this research effort ($80 million DOE, $60 million industry). The figure shows the "average" direct manufacturing costs from the project's inception through 2002 (expressed in 2002$), based on the companies' proprietary inputs. The "average" is a weighted average based on the reported production capacities, and the direct costs exclude any overhead costs (e.g., general and administrative expenses, research, and marketing/sales). The data after 2002 are projected by the companies, and again represent weighted averages. Over the 11 years of this program, the average cost has decreased by approximately 60% and U.S. production capacity has increased by sixteenfold, an annual increase of more than 30%. The data in Fig. 2 includes several different technologies (e.g., crystalline silicon, thin films, and concentrators). The average manufacturing cost for crystalline silicon participants in the program is approximately $2.00/watt in 2002.

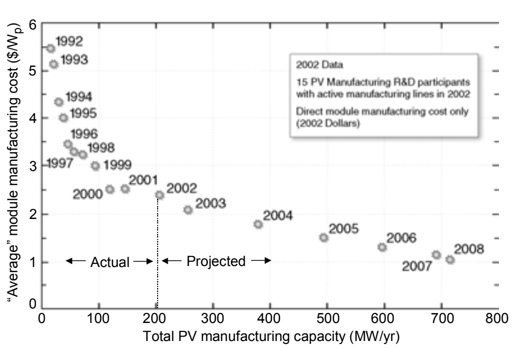

Figure 2: PV Manufacturing R&D cost/capacity data.

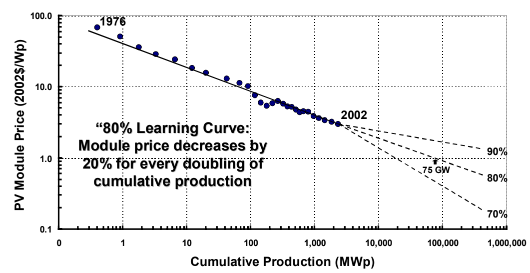

Figure 3: PV module production experience (or "learning") curve.

The third significant metric is the improvement in module reliability, as reflected in the product warranties offered by manufacturers. Today, most crystalline silicon module manufacturers offer warranties of 20 or 25 years, typically guaranteeing that the power output of the module will not decrease by more than 20% over this period. These warranties are the results of three decades of R&D progress, accelerated tests to identify failure mechanisms, and decades of experience from fielded systems. Research is ongoing to improve the reliability of thin films.

These successes in R&D are evidenced in the marketplace, where PV module *prices* have followed a historical trend along a so-called "80% learning curve." That is, for every doubling of the total cumulative production of PV modules worldwide, the price has dropped by approximately 20%. This trend is illustrated in Fig. 3. These data are based on the annual surveys conducted by *PV News* (Paul D. Maycock, Editor); the final data point for 2002 corresponds to $3.00/watt and a cumulative capacity of nearly 2,400 MW. The question, in terms of future projections, is how this price-reduction trend will continue in the future; for the 80% learning curve, a module price of $1.00/watt would be reached at a cumulative production of some 75,000 MW.

Finally, the most important trend for the PV industry is the growth of PV markets. Figure 4 shows the data based on annual surveys by *PV News*. Spurred by various incentive programs, particularly in Japan and Europe, the markets have grown by an average of more than 35% per year over the past 5 years, with more than 43% growth in 2002.

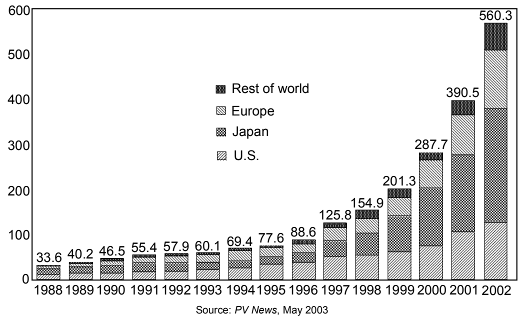

Figure 4: Worldwide PV cell/module production (MW).

These general trends over the past three decades are clearly significant, if not spectacular. Solar cell and module conversion efficiencies and reliabilities are increasing, manufacturing costs and prices are decreasing, and markets are growing at increasing rates. Next, the author will provide a perspective on key developments during each of the three previous decades.

2.2 Key Developments by Decade

The trend underlying the U.S. PV efforts has been the level of research support by the U.S. DOE and, correspondingly, the focus of the research programs over the years. As would be expected, private sector investments generally mirrored those by government, especially during times when government funding was rapidly increasing or decreasing. Figure 5 shows the history of U.S. DOE PV Program budgets by fiscal year in actual-year dollars. With inflation, the peak in the curve would be more than double in today's dollars. The designators for the respective decades shown in the figure are those of the author.

2.2.1 1973-1983: Decade of Great Expectations

The first decade of focused PV research was indeed one of great expectations, and, as it turned out, false promises. Spurred by the oil crises in the 1970s, funding increased rapidly, mostly aimed at cost reductions in crystalline silicon technology and applications development. The goal was for PV-generated electricity to be cost competitive for utility central power applications by the end of the 1980s.

The focus of this paper is on research highlights where the U.S. efforts made leading contributions, and, in fact, remain in a leadership position today, in the author's opinion. One of these areas is the discovery and development of various silicon ribbon or sheet growth processes aimed at reducing the silicon waste and slicing costs associated with silicon ingots. Most noteworthy during this period were the edge-defined film-fed growth (EFG) and the dendritic web processes, while a number of other techniques, although initially successful, are no longer being pursued. Another research accomplishment during this period was the achievement of the first >10%-efficient thin-film solar cells, e.g., Cu_2S (Institute of Energy Conversion at the University of Delaware), CdTe (Kodak), and CIS (Boeing), as well as discovery and promising early devices in amorphous silicon (RCA). The Solar Energy Research Institute was established in 1977 and became the center of U.S. PV research activities.

The center for PV technology development was the Flat-Plate Solar Array (FSA) Project established by DOE at the Jet Propulsion Laboratory (JPL). This project (from 1975 to 1985) focused on all aspects of crystalline silicon technology, from silicon feedstock to the growth of silicon ingots and ribbons to wafering to solar cell and process development to module and array design. A significant effort was expanded on developing encapsulation materials for modules and failure analysis to improve module reliability. The JPL "Block Buys" were crucial in developing module qualification tests (still in use today) and account for the reliability of today's crystalline silicon modules. By the end of this decade, there were several MW-scale manufacturing facilities in the United States (e.g., ARCO Solar and Solarex), with much of the product going into government-funded demonstration projects and to various remote (and some grid-connected) high-value applications. Although the FSA project was highly successful in a technical sense and forms the basis for much of today's successes in crystalline silicon technology, the "false promise" of this period was the expectation that large, utility-scale, cost-competitive PV electricity would be realized by the end of the 1980s. Decreasing oil and gas prices, and the resulting decrease in interest in alternative energy sources (as reflected in the precipitous decrease in government funding at the end of this period), were some of the factors hindering further progress in PV technology and markets.

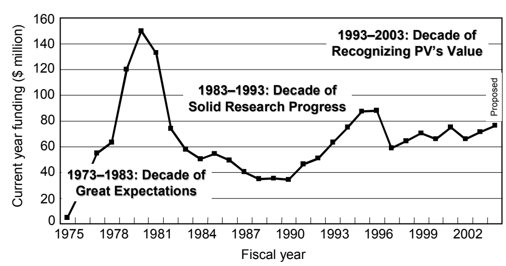

Figure 5: U.S. DOE PV Program budget history (not adjusted for inflation).

2.2.2 1983-1993: Decade of Solid Research Progress

The DOE Program funding was aimed at long-term, high-risk (but high-payoff) research during this period, with funding at a fraction of that in 1981. Despite the reduced funding, this was a decade of solid research progress, albeit accompanied by a general feeling of "who needs PV" (or renewables) caused by decreasing energy prices. There was continued rapid progress on the research front in developing silicon ribbon and sheet technologies, with the EFG process (Mobil Solar, followed by ASE Americas, and now RWE Schott Solar), the Silicon Film™ process (AstroPower), and the String Ribbon process (Massachusetts Institute of Technology, A.D.

Little, and now Evergreen Solar) becoming the most promising technologies. The research efforts resulted in achieving the first >20%-efficient crystalline silicon solar cells (Stanford University and UNSW) and the first >12%-efficient CIS (Boeing and ARCO Solar) and CdTe (University of South Florida) solar cells. SERI was formally designated a DOE national laboratory (NREL) in 1991, and NREL researchers achieved the first >25%-efficient multijunction III-V solar cells.

The markets for PV were growing slowly during this period, with remote, off-grid, high-value applications (e.g., communications) being most prominent. Markets in developing countries (mostly off-grid rural) were also growing, as were the applications of PV (mostly amorphous silicon) in small consumer products. The manufacturing base for PV expanded some to meet the demand, mostly based on the successful JPL/FSA programs. The first large-scale manufacturing of amorphous silicon was demonstrated for consumer products in Japan, and later for early power modules in the United States. Some large utility-scale systems were built in the U.S. (resulting from favorable incentives), but many have since been dismantled due to various technical problems. It was only during the latter part of this period that concerns over energy and the global environment started to come to the forefront again, resulting in increasing U.S. budgets (see Fig. 5) and rapidly increasing budgets in Europe and particularly in Japan.

2.2.3 1993-2003: Decade of Recognizing PV's Value

The most recent decade may be termed the "renaissance" of photovoltaics, with the potential current and future value of PV finally becoming recognized worldwide. However, this recognition came with a price tag, with substantial subsidy and other incentive programs aimed at "buying down" the cost of installed PV systems in Japan and Europe, and more recently in the U.S. (mostly state-based rather than federal programs). The DOE PV Program funding was generally stable in this period, and increased slightly in recent years. The program has been balanced between fundamental and applied research, technology development, and some market facilitation, with a focus on thin-film technologies and manufacturing R&D. Research activities were closely aligned with the *U.S. Photovoltaic Industry Roadmap* for 2000-2020, which projects a 25%-per-year growth in PV markets with significant growth in U.S. domestic markets [1].

Research progress during this period has been nothing short of spectacular, from 24.7% efficiency achieved in crystalline silicon (UNSW), to 19.2% achieved in CIGS (NREL), to 16.5% achieved in CdTe (NREL), to more than 35% achieved in triple-junction concentrator cells (Spectrolab). New processing techniques for crystalline silicon (e.g., rapid thermal processing by Georgia Institute of Technology) and novel deposition approaches for thin-film technologies (e.g., hot-wire deposition of amorphous silicon by NREL and others) were just some of the exciting developments. A number of new, promising PV technologies are emerging (e.g., dye-sensitized cells, organic and polymer cells, nanostructures), and, overall, the fundamental understanding of PV materials, devices, and processes has improved. Continuing to build the scientific base, especially for the newly emerging PV technologies, has remained a program emphasis, because the achievement of the ultimate efficiencies in these materials will require such fundamental understanding.

To meet the demand of rapidly growing markets, there have been ongoing expansions of both ingot-based and ribbon-based crystalline silicon technologies in the U.S. and worldwide, with several >100-MW manufacturing plants either in place or under development. In 2002, as in prior years, crystalline silicon modules dominated the market with nearly 90% market share. Thin-film technologies progressed to first-time manufacturing (from a few MW to a few tens of MW), with initial niche products for building-integrated PV being most evident. Concentrator technologies (up to a MW) are being used in small utility systems. On the negative side, the decade has seen many corporate turnovers in thin-film technologies resulting from various manufacturing, reliability, and marketing issues for thin films.

As described earlier (see Fig. 4), market growth has been phenomenal during this period. While it took until 1999 to reach 1000 MW cumulative installed systems worldwide, it took less than three years to more than double this figure. The large market-incentive programs (subsidies, buy-downs, and policies) in Japan and Europe and some state (and some federal) incentives in the United States continue to drive the growth in the markets, with a focus on residential and commercial buildings. Applications and markets in developing countries, especially in India and China, are continuing to thrive. Installed system costs have decreased, but the trend has slowed in recent years.

The evidence shows that progress in PV has been remarkable over the past 30 years and that all the relevant trends (see Figs. 1 to 4) are heading in the right directions. One might readily project that PV will play an increasing role in providing clean, inexhaustible energy worldwide.

3. LOOKING AHEAD 20 YEARS

Capturing 30 years of progress in a short paper has been difficult, but attempting to predict the future is much harder and certainly more controversial. Again, the reader is reminded that the opinions expressed herein are strictly those of the author, based on his 30-year experience in the technology and the biases that often accompany such lengthy involvement. One of these biases is a sense of "conservatism" toward predicting the future. The author's experience is that "overnight successes" simply do not happen and that "breakthroughs" are neither predictable nor can they form the basis for long-term planning. Even for a technology that looks very promising in its early stages, it takes time, a great deal of commitment and talent, significant financial resources, and a great deal of luck (as well as good timing) for the technology to succeed.

Three scenarios for the future of photovoltaics are described below, each associated with the technologies that form the core of the research and market activities today. The scenarios will be presented in the order of *decreasing probability of success* that also considers the timing when these scenarios are likely or projected to have in impact. Prior to these scenarios, a brief summary is provided of balance-of-systems issues and projections.

Table 1: A simple model for module efficiency impacts on module cost.

Wafer Cost ($\$/m^2$)	Cell Process Cost ($\$/m^2$)	Module Process Cost ($\$/m^2$)	Module Efficiency (%)	Module Manufacturing Cost ($/watt)
W_{hi}	$C \times W_{hi}$	$M \times W_{hi}$	η_{hi}	$W_{hi}(1 + C + M)/1000\eta_{hi}$
W_{low}	$C \times W_{hi}$	$M \times W_{hi}$	η_{low}	$(W_{low} + W_{hi}[C + M])/1000\eta_{low}$
Equating manufacturing costs: $\mathbf{W_{low}/ W_{hi} = 1 - (1 - \eta_{low}/\eta_{hi}) (1 + C + M)}$				

3.1 Projections for Balance-of-Systems Costs

A significant part of the cost of PV systems is the balance-of-systems (BOS) components. These include power-related hardware, such as inverters, batteries, and charge controllers, as well as area-related costs, such as wiring and interconnections, installation, and site preparation. These costs are usually a significant portion (more than half) of the system cost today for many "one-of-a-kind" and off-grid installations. However, the costs are lower for repetitive applications and high-volume installations. For today's residential PV systems in Japan, for example, the BOS costs comprise approximately one-third of the installed system cost. It is also a known fact that many problems with today's PV systems, particularly in remote areas and some developing country applications, are associated with failures of the BOS components. With the PV module expected to last 20-25 years, such failures are often interpreted as a failure of PV itself. With good system design, proper component selection, trained installers, and proper procedures, PV systems are reliable today – some manufacturers offer warranties of 10 years on the entire PV system. It is not unreasonable that some BOS components (e.g., inverter) may continue to need periodic replacement as part of the overall operation-and-maintenance costs for the PV system.

BOS costs are expected to continue to decline for both power-related and area-related components. This will occur with still larger markets and repetitive applications, standardized system designs and components, certified components and systems, very large-volume manufacturing of the power-conditioning components, sound system engineering for improved reliability, and training and certification of installers. These are all areas where technical activities are supported by the PV programs in various countries. In the author's opinion, total BOS costs of <$1.00/watt and potentially <$0.50/watt should be achievable in the next decade. In any case, BOS issues will not be the ultimate technical "showstoppers" for large-scale PV applications and markets – but PV module price and performance can be the limiting factors.

3.2 The Pragmatic (and Realistic) Scenario

The *most probable* scenario is that wafer-based crystalline silicon technologies (both from ingots and ribbons/sheet) will continue to dominate the markets for the next decade and probably longer. Silicon feedstock is not expected to be a problem; there should be sufficient, high-quality silicon available at reasonably low cost – a supply/demand issue the marketplace will continue to resolve. With the increasing emphasis on higher efficiencies, as discussed below, low-quality, "solar-grade" silicon will likely not have an impact, unless that feedstock can be used to grow high-quality silicon wafers. Efforts at reducing silicon use, such as with thinner wafers and ribbons, will succeed to some extent, ultimately limited by processing tradeoffs. This will negate, to a large extent, the cost issue associated with silicon feedstock.

The key to continued progress will be improving module efficiencies (as well as reducing module manufacturing costs). A simple analysis of the impact of module efficiencies is illustrated in Table 1. Assume the cost of a high-quality wafer, ready for cell production, is W_{hi} (in units of $\$/m^2$). The cell and module process costs will be some multiplying factor times this amount, say C and M, respectively. For a resulting module efficiency of η_{hi}, the module manufacturing cost (in $/watt) is shown in the last column of the table. Suppose one substitutes a lower cost (and lower quality) wafer, costing W_{low} in $\$/m^2$, into the same process sequence for cells and modules. To a first approximation, it will cost the same amount, on a $\$/m^2$-basis, to process this wafer, resulting in the lower efficiency and the manufacturing cost shown in the table. Equating the two manufacturing costs, one obtains the expression shown in the last line of Table 1. Typical values of the factor C range from 0.6 to 1.2, whereas M is usually between 1 and 2, with $C + M \approx 2$. One can substitute any sets of low and high efficiencies into the expression in the table and arrive at startling results: for 8% and 12%, for example, the low-cost wafer needs to be "free"; for 9% and 13%, the low-cost wafer needs to be $1/13^{th}$ the cost of the higher-efficiency wafer. This analysis ignores the significant impact of module efficiency on system cost.

The simplified conclusions from this analysis are: (1) for a given cell and module process, one should use a wafer resulting in the highest efficiency and not necessarily the "cheapest" wafer; and (2) for a given wafer technology, one should use cell and module processes resulting in the highest efficiency and not necessarily the "cheapest" processes. Of course, there will be cost/efficiency tradeoffs to consider, which can best be handled by the more sophisticated manufacturing cost models used by manufacturers.

The expected progress in module efficiencies and costs will occur, but it is not likely that these technologies will continue to follow the "80% learning curve"; in fact, the author projects that module prices will gradually decrease and asymptote somewhere in the $1.20 to $1.50/watt range (in 2002$). This is illustrated in Fig. 6 by the top portion of the extrapolation beyond 2002. In this scenario, installed system costs will be in the $1.70 to $2.20/watt range. This will result in huge, sustainable markets for PV, albeit unlikely to be energy significant until beyond 2050. The future-year markers on the curve (for 2013 and 2023) are based on 25% annual growth rates – it is unlikely that these rates will be maintained in this scenario (markers will shift to the left). Market incentives, such as buy-downs, tax credits, regulatory, and policy incentives will be very important and will enhance market growth, particularly in the near term.

3.3 The Optimistic (but Probable) Scenario

The second scenario, deemed to be less likely but still *probable*, is based on the successful resolution of the critical technical (as well as marketing) issues for the next-generation technologies, namely thin films and concentrators. This is the primary focus of ongoing R&D programs. For thin films, the technical issues include module efficiency, manufacturing scale-up, yield, and throughput, and, most importantly, module reliability. Neither environmental safety and health concerns nor materials availability are likely to limit the large-scale application of thin-film technologies – the key is education and early recognition of and response to these issues. For concentrators, manufacturing scale-up for high-efficiency cells and optical components, and long-term reliability are key technical issues to be resolved. Assuming the research efforts succeed, these next-generation technologies are expected to gain market share gradually, especially during the latter part of the decade and into the next decade. Technologies with "niche" market applications (e.g., flexible or semitransparent thin films for building integration) will have significant early-market advantages to help them through the transition period to become competitive with crystalline silicon. The most important factor for success, in the author's opinion, will be the commitment and the financial resources of investors toward addressing all the technical and marketing issues.

In this scenario, the module price "learning curve" can be significantly affected, as illustrated by the middle portion of the extrapolation in Fig. 6, especially with successful large-scale manufacturing. This is expected to occur around the 2007-2012 timeframe, with module prices ultimately reaching values as low as $0.50/watt in the future. This will result in huge, sustainable, and energy-significant markets for PV by 2030 or sooner. The future-year markers in Fig. 6 may, in fact, shift to the right, with market growth rates exceeding 25%. With PV system costs as low as $1.00 to $1.50/watt in this scenario, one can envision large-scale applications for PV to serve the entire energy sector (e.g., hydrogen generation for transportation). Market incentives should not be necessary in this scenario, particularly into the next decade. However, large-scale concentrator systems may require regulatory incentives (e.g., mandatory "portfolio" requirements for utilities in areas where concentrator systems are attractive). Unlike thin films and crystalline silicon, concentrators are not likely to impact the distributed markets such as residential and commercial buildings.

3.4 The "Wishful Thinking" Scenario

One might term this the *visionary* scenario, based on yet-to-be-researched or discovered technologies. There is no doubt that ongoing exploratory research on future, "third-generation" PV technologies is very important and will have significant benefits. It can result in a better fundamental understanding of the limitations to current and next-generation technologies. There is always the potential for the discovery of new materials, new devices, new processing techniques, and, in fact, new physics of device operation. These may result in "breakthroughs" in cost and efficiency, well beyond what we can project with today's and the next-generation technologies. There are many examples of such exploratory research, both in the U.S. programs and worldwide. The High Performance Photovoltaics project at NREL has the goal of doubling the efficiencies of today's flat-plate and concentrator modules. Research on nanostructures, quantum dots, and defect-layer solar cells may result in ultrahigh efficiency devices. Ultralow costs may be achieved with organic and polymer solar cells, for example, as well as with ultrahigh-throughput and ultralow-cost manufacturing processes.

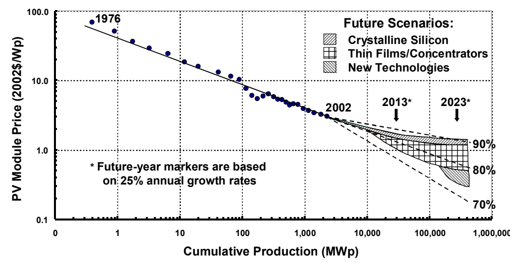

Figure 6: Extrapolations of the PV module price "learning curve" for different future scenarios.

If some (or any) of these new technologies succeed, the module "learning curve" can be significantly impacted, as illustrated in Fig. 6. It is not possible to predict if and when this scenario will occur; in the author's opinion, these technologies will not have an impact until 2020 or beyond. While the "success" of PV does not require these ultimate discoveries, scientific research and discovery are the foundations for technological progress.

4. CONCLUSIONS

Photovoltaic technology has made significant progress in just 30 short years, and the same – and more – can be expected in the coming decades. Although the opinions expressed in this paper are strictly those of the author, and, as such, do not represent the views of DOE or NREL, the future projections herein are not inconsistent with overall program directions and priorities in the DOE PV Program. Crystalline silicon research is aimed at improving module efficiencies and lowering costs through a better fundamental understanding of defects, impurities, and device processing, and through manufacturing R&D. The major program emphasis is on next-generation technologies, primarily thin films, as these offer the greatest potential for significant cost reductions in the foreseeable future. Finally, ongoing exploratory research is aimed at the discovery of future-generation PV technologies.

REFERENCES

[1] *Solar Electric Power: The U.S. Photovoltaics Industry Roadmap* (Published by the U.S. PV Industry, May 2001).

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